A Numerical Study for Damage Detection of a Thin Plate Using Macro-Strain Measurement

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Abstract
Plate structures are widely used as important structural components in many engineering applications, hence structural condition assessment of in-service plate structures plays an important aspect of global structural health monitoring. Recently, vibration-based structural damage detection techniques that perform damage diagnosis of a structure based on its structural dynamic characteristic parameters attracted great attention in the research community. Among the vibration-based features, modal curvature-based damage indices have been applied to many beam-like structures owing to their simplicity and sensitivity to damage. The application of these damage indices to plate structures is mainly based on the measurement of out-of-plane vibration by a laser scanning vibrometer. However, mode shapes identified from out-of-plane vibration data are unavoidably masked by measurement noises and the numerical differentiation procedure further deteriorates the performance of modal curvature-based methods. Recently, long-gauge FBG sensors have been proposed to measure dynamic macro-strain data for obtaining modal curvature of a beam-like structure. The direct measurement of curvature can circumvent the numerical problem caused by differential of out-of-plane data with noise. In this study, the macro-strain measurement is applied to detect damage of a plate structure. A numerical model of a rectangular thin plate with two sides fixed is constructed. The modal curvature method (MC), modal curvature squared method (MCS) and the damage index based on modal strain energy (DI) are used to find the damage locations. The results show that only the DI method could successfully localize the damage regions if the stiffness of these regions are affected substantially by the simulated damage.

1 INTRODUCTION
Plate structures are widely used as important structural components in many engineering applications such as civil, mechanical, aerospace, and automotive engineering. Structural condition assessment of in-service plate structures plays an important aspect of global structural health monitoring. Recently, vibration-based structural damage detection techniques that perform damage diagnosis of a structure based on its structural dynamic characteristic parameters attracted great attention in the research community. Among the studies on damage detection methods, the studies on the damage detection method for two-dimensional (2-D)
plate-type structures are relatively limited. Cawley and Adams [1] were probably the first to detect damage of a rectangular plate using frequency shifts. Many other methods to detect damage of a plate-like structure has also been proposed based on finite element models, such as Dos Santos et al. [2] and Ge and Lui [3]. On the other hand, some of the methods which detect damage of a plate-like structure without any information of a finite element model. Cornwel et al. [4] used damage index based on fractional strain energy calculated from measured mode shapes with large amount of points to locate damage of a plate. Bayissa and Haritos [5] proposed a method to use spectral strain energy derived from moment-curvature response to detect damage of a plate-like structure. Thus the damage locations can be identified using non-mass-normalized mode shapes and natural frequencies without a finite element model.

It has been shown that changes in the strain mode shapes are more sensitive to the structural changes than the changes in the displacement and curvature mode shapes. [6] However, conventional foil strain gauges are not suitable for large-scale civil SHM not only because of lack of stability, durability, and long-term reliability, but also for their inability to reflect the influence of damage effectively unless located at the damaged region. On the other hand, fiber Bragg gratings (FBG) sensing strategies can provide flexibility and practicality. Compared with mechanical sensors, they are light, compact, flexible, immune to electromagnetic interference, easy to install, and can be easily multiplexed in a large-scale distributed sensing network [7]. Moreover, modal parameters identified from macro strain time series using long gauge FBG sensors have been successfully used for damage localization [8]. Therefore, in this article, the modal strain algorithms are used to detect damage of a plate structure on the basis of dynamic strain measurements from long-gauge FBG sensors.

2 METHODOLOGY OF MODAL CURVATURE-BASED DAMAGE DETECTION METHODS

Because modal curvature-based damage indices are damage-sensitive, spatial-specific and simple to use among vibration-based features, they are good candidates for structural damage identification (Pandey et al., 1991; Abdel Wahab and De Roeck, 1999). The curvature along certain direction can be measured by employing the long-gauge FBG sensors attached onto the surface of a plate element between two adjacent nodes. The modal curvature \( \kappa_m \) of an element corresponding to the \( m^{th} \) long-gauge sensor can be obtained directly from the macro-strain measurement \( \delta_m \) as

\[
\kappa_m = \frac{\delta_m}{h_m}
\]

where \( h_m \) is the distance between the inertia axis of the FBG sensor and the inertia axis of the plate. Note that the shear deformations are neglected and the deformation behavior of the plate is simplified in accordance with Kirchhoff Plate Theory.

As for damage detection using curvature, Pandey et al. (1991) propose modal curvature (MC) method on the premise that, for a bending moment applied to a structure, a reduction of stiffness associated with damage will increase the curvature. The Modal Curvature damage
index (MC) is defined as:

\[ MC_i = \frac{1}{h_m} \sum_r \Delta \delta_{m_ir} = \frac{1}{h_m} \sum_r \left| \delta_{m_ir}^d - \delta_{m_ir} \right| \]  

(2)

where \( i \) and \( r \) are the indices for measurement location and mode, respectively, and the superscript \( (d) \) represents damaged structure. The location of the damage is assessed by the largest computed absolute changes in modal curvatures of the damaged and undamaged structure.

Ho and Ewins (2000) also present mode shape curvature squared method as an improvement on the MC method to make the location of damage more distinct. The Modal Curvature Squared damage index (MCS) is defined as:

\[ MCS_i = \frac{1}{h_m} \sum_r \Delta \delta_{m_ir}^2 = \frac{1}{h_m} \sum_r \left| \left( \delta_{m_ir}^d \right)^2 - \left( \delta_{m_ir} \right)^2 \right| \]  

(3)

Damages are localized at the elements with significant absolute difference between the MCS of damaged and intact structures.

Stubbs et al. (1995) develop a damage index (DI) that utilizes the modal strain energy before and after damage to locate and possibly estimate the extent of damage in flexural structures for which few mode shapes are available. The DI is modified to avoid some numerical complications that may arise when the strain energy contribution of the \( i \)th element of the undamaged structure is very small. The damage index is defined as:

\[ MCS_i = \frac{1}{h_m} \sum_r \Delta \delta_{m_ir}^2 = \frac{1}{h_m} \sum_r \left| \left( \delta_{m_ir}^d \right)^2 - \left( \delta_{m_ir} \right)^2 \right| \]  

(4)

The elements with positive DI value represent the possible damage locations of the structure.

3 NUMERICAL STUDIES

In this study, a thin plate model was constructed via ANSYS software as shown in Figure 1 to verify the modal curvature based methods. The dimension of the plate was 1512mm×1512mm×3mm. The left side of the plate was connected to a side plates whose dimension was 1550mm×150mm×12mm and the side plates was stiffened by a H-beam whose height, width, web-thickness, flange-thickness were 1500mm, 150mm, 10mm, and 7mm, respectively. The bottom side of the plate was connected to another side plate whose dimension was 1612mm×150mm×12mm and the side plate was fixed. The elastic modulus, the Poisson’s ratio and the density of the finite element model was \( 2.0 \times 10^{11} \) N/m², 0.33 and \( 7.8 \times 10^3 \) kg/m³, respectively. Eighteen long-gauge FBG sensors numbered as S1 to S18 were
assumed to be installed onto one side of the thin plate via aluminium brackets. The stiffness contributed by the long-gauge FBG sensors were simulated by springs with longitude stiffness 11,319N/m. The plates and H-beam were constructed using shell elements while the brackets were constructed using solid elements. Totally 54,759 elements with 82,471 nodes were generated.

Figure 1. The thin plate model constructed via ANSYS software. Eighteen long-gauge FBG sensors numbered as S1 to S18 were installed onto one side of the thin plate via aluminium brackets.

Figure 2. A vertical cut was generated under the long-gauge FBG sensor S10 in Damage Case 1.
The damage was simulated by cutting the thin plate with 200mm length and 5mm width. Four damage cases were simulated as summarized in Table 1. In the Damage Case 1, a vertical cut was generated under the long-gauge FBG sensor S10 as shown in Figure 2. In the Damage Case 2, a vertical cut was generated at the center of the zone surrounded by the long-gauge FBG sensors S1, S10, and S13 as shown in Figure 3. In the Damage Case 3, a vertical cut was generated under the long-gauge FBG sensor S12. In the Damage Case 4, a vertical cut was generated under the long-gauge FBG sensor S16 and another horizontal cut was generated under the long-gauge FBG sensor S11.

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage Case 1</td>
<td>S10</td>
</tr>
<tr>
<td>Damage Case 2</td>
<td>S1 · S10 · S13</td>
</tr>
<tr>
<td>Damage Case 3</td>
<td>S12</td>
</tr>
<tr>
<td>Damage Case 4</td>
<td>S6 · S11</td>
</tr>
</tbody>
</table>

Table 1. Damage locations in each damage cases.

The macro-strain of the $i^{th}$ long-gauge FBG sensor $\delta_{m_{ir}}$ of the $r^{th}$ mode was calculated using the modal displacement at both ends of the long-gauge FBG sensor by $\delta_{m_{ir}} = (\varphi_{m_{ir}}^a - \varphi_{m_{ir}}^b)/l_{mi}$, where $\varphi_{m_{ir}}^a$ and $\varphi_{m_{ir}}^b$ represented the modal displacement at each end respectively and $l_{mi}$ represented the length of the $i^{th}$ long-gauge FBG sensor.

The modal curvature was calculated using these macro-strain measurement with Equation (1). The MC, MCS, and DI damage indices were calculated using Equation (2), (3), and (4) respectively. It was evident that the damage location of all the Damage Cases using the MC and MCS damage indices were confusing and failed. Therefore, only the results of the DI approach were shown in this study.

The results of Damage Case 1 using the first mode to detect damage by the DI method is...
shown in Figure 4. It is evident that the most possible location of damage is around S10 since its DI is the largest. The other possible damage locations are around S13, S5, S6, S4, and S1 since their DI are also relatively large comparing to other locations. The damage localization using the first mode seems quite acceptable because the real damage location, i.e. around S10, is identified clearly, but with some other false-positive damage locations. However, when more than one modes are used to detect damage of Damage Case 1, the results become quite confusing as shown in Figure 5 where the results using the first two modes to the first six modes are also included. Observing the mode shape of the second mode as shown in Figure 6, it is found there is a significant discontinuity along the vertical cut around S10. It is concluded that the modes with significant discontinuity should be avoided to use because using the modes with such discontinuity may lead to confusing damage localization results.

Figure 4. The damage index results of Damage Case 1 using the first mode.

Figure 5. The damage index results of Damage Case 1 using the first two modes to the first six modes.
The DI of Damage Case 2 using the first mode to the first six modes to detect damage is shown in Figure 7. Although the DI values of most of the locations using different number of modes are not consistent, the DI values of the S13 and S10 are consistently larger than other locations. Therefore, the most possible damage locations could be around S10 and S13. Actually, the real damage location is surrounded by S1, S10, and S13. It is reasonable that the DI values of the S1 are relatively small because the stiffness of the plate around S1 sensor is not significantly affected by the vertical cut of damage.

The DI of Damage Case 3 using the first mode to the first six modes to detect damage is shown in Figure 8. Again, although the DI values of most of the locations using different number of modes are not consistent, the DI values of the S12 are consistently larger than other locations. Therefore, the most possible damage locations could be around S12, while the real damage location is under S12. Unlike the confusing results using different modes in Damage Case 1 due to mode shape with significant discontinuity, the results in Damage Case 3 is quite consistent using the first six modes, probably because there are no significant discontinuity in the first six mode shapes.
Figure 8. The damage index results of Damage Case 3 using the first one mode to the first six modes.

The DI of Damage Case 4 using the first mode to the first six modes to detect damage is shown in Figure 9. Among the DI values at different sensors using different number of modes, the DI values of the S6 and S11 are consistently the largest ones. Therefore, the most possible damage locations could be around S6 and S11, while the real damage location are under these two sensors. However, the DI values of the S2 and S15 are also consistently and larger than the rest locations. It may be because the stiffness of the plate around S2 and S15 sensors are affected by the damage. Besides, no confusing results using different modes are observed in this damage case due to mode shape with significant discontinuity.

Figure 9. The damage index results of Damage Case 4 using the first one mode to the first six modes.

4 CONCLUSIONS

In this study, the macro-strain measurement is applied to detect damage of a plate structure. The long-gauge FBG sensors are used to directly measure dynamic macro-strain data for obtaining modal curvature of a plate structure. A numerical model of a rectangular thin plate
with two sides fixed is used to verify the proposed idea for damage detection of the plate. The modal curvature method (MC), modal curvature squared method (MCS) and the damage index based on modal strain energy (DI) are used to find the damage locations. The results show that only the DI method could successfully localize the damage regions if the stiffness of these regions are affected substantially by the simulated damage. However, sometimes the mode shapes with significant discontinuity could exist in the first few fundamental modes and the results of DI method using these modes could be confusing.

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